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Fishery stock assessments often attempt to provide future projections of population abundance and landings on which management decisions can be based. However, uncertainties in estimating the relationship between spawners and recruits, that drive such projections, are often considerable. The purpose of this study is to compare two relationships for characterizing these uncertainties using simulated projections of future population abundance with an age structure model for Atlantic menhaden data. One relationship is based on a mathematical spawner-recruit relationship (Ricker model). An alternative relationship reduces spawners and recruits to discrete categories, and estimates conditional probabilities to determine subsequent recruitment from spawning biomass (Event Tree risk analysis). Six biological "trigger" variables and activation levels for the Atlantic menhaden population are under consideration by the Atlantic States Marine Fisheries Commission. The first five variables serve as biological reference points for the simulations. The last variable, maximum spawning potential (MSP), defines constant levels of fishing mortality for each simulation. Four of the five biological reference points suggest greater risk associated with the Ricker relationship than that associated with the Event Tree relationship at the 1980's level of fishing mortality (MSP of 4.5%). A large decrease in risk associated with spawning stock biomass from the Ricker relationship was obtained with an MSP of 10%, with little decrease in risk available from further decreasing fishing mortality to obtain an MSP of 20% or higher. Gradual declines in risk associated with spawning stock biomass from the Event Tree relationship was obtained as fishing mortality was decreased to correspond to an MSP level of 10%, 20% and 30%.

Les évaluations de stock de pêche tentent souvent d'offrir des prévisions de l'abondance de population et des quantités débarquées en vue d'étayer les décisions de gestion. Toutefois, les incertitudes d'estimation de la relation entre les géniteurs et les recrutés, sur laquelle reposent ces prévisions, sont souvent considérables. L'objectif de cette étude est de comparer deux relations afin de caractériser ces incertitudes à l'aide de prévisions simulées de l'abondance de la population future selon un modèle de structure d'âge avec les données décrivant l'alose tyran. Une de ces relations s'inspire de la relation mathématique entre les géniteurs et les recrutés (modèle de Ricker). Une autre relation réduit les géniteurs et les recrutés en catégories discrètes et évalue les probabilités conditionnelles de détermination du recrutement futur selon la biomasse génitrice (analyse du risque par arbre d'événements). Six variables de «déclencheurs» biologiques et niveaux d'activation pour la population d'alose tyran sont actuellement en cours d'étude par l'Atlantic States Marine Fisheries Commission. Les cinq premières variables servent de points de référence biologiques des simulations. La dernière variable, le potentiel géniteur maximum (PGM), définit les niveaux constants de mortalité par pêche pour chaque simulation. Quatre des cinq points de référence biologiques laissent croire en un risque plus élevé avec la relation de Ricker qu'avec la relation de l'arbre d'événements, selon le niveau de mortalité par pêche des années 1980 (PGM de 4,5 %). Une importante diminution du risque a été notée, dans le cas de la biomasse génitrice de la relation de Ricker, avec un PGM de 10 % et avec une très faible diminution du risque associée à la réduction additionnelle de mortalité par pêche pour obtenir un PGM de 20 % ou plus. Un déclin graduel du risque associé à la biomasse génitrice à partir de la relation de l'arbre d'événements a été obtenu lorsque la mortalité par pêche était réduite pour correspondre aux niveaux de PGM de 10 %, de 20 % et de 30 %.

To predict future population levels of fish stocks, it is necessary to understand the relationship between spawning stock and subsequent recruits to the fishery. Unfortunately, it is difficult to obtain a reasonable mathematical relationship between spawners and recruits for most fish stocks. Even if "statistically significant", the fit of spawner-recruit data to a mathematical relationship has large error remaining unexplained by the model.

My purpose in this study is to compare two relationships for relating spawning stock biomass and subsequent recruits to age 0 (about six months of age) using Monte Carlo population simulations. The first relationship is based on fitting the historic spawner and recruit data to the Ricker model (Ricker 1975) using nonlinear regression techniques (SAS Institute Inc. 1987), and estimating the parameters for the corresponding normal distribution of the residuals.

The second relationship is based on Event Tree risk analysis (Brown and Patil 1986; Linder et al. 1987), by which spawners and recruits are each divided independently into three categories (low, medium, high) and then the conditional probability is estimated for each recruit category conditioned on the spawner category. Actual values for recruits are then randomly selected from distributions for the three recruit categories.

Parameters of the Ricker spawner-recruit model and conditional probabilities for the Event Tree relationship are estimated from data available from the Atlantic menhaden stock (Vaughan and Smith 1988; Vaughan 1990). Biological reference points based on five of six biological "triggers" adopted by the Atlantic States Marine Fisheries Commission's (ASMFC) Atlantic Menhaden Board (AMB) are used to compare replicate 12-year simulations using these two relationships based on different levels of instantaneous fishing mortality rates (related to the sixth trigger).

In this study, the Atlantic menhaden and six triggers are briefly described. Next, the parameter estimation for the two spawner-recruit relationships and population projections are described. Projections are compared for two spawner-recruit relationships and different levels of fishing mortality rates (as related to the sixth trigger). Finally, the significance of the results are discussed with respect to limitations in conducting the simulations and what management conclusions can be drawn.

Atlantic Menhadden Fishery

Atlantic menhaden *(Brevoortia tyrannus)* is a euryhaline species found in coastal and inland tidal waters from Nova Scotia, Canada, to West Palm Beach, Florida (Reintjes 1969). Adult menhaden are filter feeders, feeding primarily on phytoplankton, and in turn supporting predatory food fishes. A commercial fishery for Atlantic menhaden has existed since colonial times, but purse seines, now the principal gear, were introduced by 1845 (Frye 1978). Large carrier vessels are equipped with a pair of purse boats for setting the seines around the schools of fish. In 1990, five active reduction facilities on the Atlantic coast, including shore based plants in North Carolina (1 plant), Virginia (2), New Brunswick, Canada (1), and an internal waters processing agreement in Maine with the Soviet factory ship Riga, processed the fish into meal, oil, and solubles (Vaughan 1990).

Management of Atlantic menhaden in the United States is by the individual U.S. Atlantic coastal states as coordinated through the ASMFC. The ASMFC's AMB recently approved (August 5, 1992) six biological reference or "trigger" variables devised by the ASMFC's Atlantic Menhaden Advisory Committee (AMAC). When these estimated variables are compared to pre-selected values, and at least one variable is found to lie in a "danger zone", then a meeting of AMAC will be held to determine whether corrective action is needed. In the committee's discussions all six trigger variables and any relevant ancillary information will be considered.

The six biological "trigger" variables are: (1) annual landings in weight below 250,000 t, (2) proportion of age 0 menhaden in the landings by number above 25%, (3) proportion of adult menhaden (age 3 and older) in the landings by number above 25%, (4) recruits to age 1 below 2 billion, (5) spawning stock biomass below 17,000 t, and (6) percent of maximum spawning potential below 3%. Annual data for the first three trigger variables are available soon after the end of the fishing season. The other trigger variables are obtained from output produced in a virtual population analysis (VPA).

The first three triggers are subject to the potential for "false firing", because values in the "danger zone" do not necessarily imply that something is wrong with the Atlantic menhaden stock. Ancillary information is important to judge whether the "firing" of these triggers requires some action by the committee. The final three triggers are also subject to "false firing", but for a different reason than for the first three triggers. Recent estimates from the virtual population analysis are subject to large uncertainty. However, estimates more than 2 or 3 years old are generally more accurate. If the estimates are accurate and precise, then "firing" of these trigger variables reflect a real problem in the Atlantic menhaden stock.

Generally, the interquartile range of the historical data from 1965 through 1990 was used to select the particular trigger value for each variable (Table 1). The value for the third trigger is based on historical data from 1955 through 1990 to include the stock collapse during the 1960's. The first, fourth, fifth, and sixth variables are triggered if the respective values fall below the 25th percentile (or similar value). The second variable is triggered if the respective values fall above the 75th percentile.

Atlantic menhaden landings were selected because they could be an indicator of a change in stock abundance. Estimates are available from 1940 through 1990 (Table 1). They peaked in the late 1950's, collapsed during the 1960's, and improved somewhat during the 1970's. An awareness of whether economic conditions have drastically reduced the fishing activity, as in 1986 when a major plant closed, would be important ancillary information.

The proportion of age 0 menhaden in the landings by numbers was selected because of two concerns. First, very high harvest of the youngest fish may reduce potential yields based on a yield per recruit or "growth overfishing" argument (Vaughan and Smith 1988, 1991). Second, although the catch of age 0 menhaden is highly weather dependent, a large harvest of these fish in years of poor recruitment may greatly reduce subsequent spawning stock biomass. These data are available from 1955 through 1990 (Table 1).

Proportion of adult (age 3+) menhaden in the landings by number was also selected because of two concerns. First, it may result in a short-term reduction of the adult spawning stock. Second, large landings of adults relative to subadults may indicate the potential for recruitment failure as in 1961 and 1962, as the huge 1958 year class attained the age of 3 and 4, respectively, and recruitment for the following years were poor. Hence, a large showing of adult menhaden by numbers

Table 1. Annual estimated values of six Atlantic menhaden triggers, 1940–1990.

Year	Landings[a]	P0[b]	P3+[c]	Recruits[d]	SSB[e]	MSP[f]
1940	179.0	-	-	-	-	-
1941	283.1	-	-	-	-	-
1942	167.4	-	-	-	-	-
1943	215.0	-	-	-	-	-
1944	243.5	-	-	-	-	-
1945	285.6	-	-	-	-	-
1946	351.8	-	-	-	-	-
1947	376.4	-	-	-	-	-
1948	341.3	-	-	-	-	-
1949	363.4	-	-	-	-	-
1950	311.2	-	-	-	-	-
1951	351.3	-	-	-	-	-
1952	423.6	-	-	-	-	-
1953	589.2	-	-	-	-	-
1954	617.9	-	-	-	-	-
1955	644.5	24.4	20.1	3.1	325.4	13.8
1956	715.4	1.0	15.5	5.7	257.3	6.6
1957	605.6	8.5	7.1	7.3	132.6	6.7
1958	512.4	3.9	4.4	3.3	88.3	16.1
1959	662.2	0.2	8.4	15.1	172.9	8.6
1960	532.2	2.6	7.7	2.2	122.7	24.1
1961	578.6	0.0	48.6	3.0	358.6	13.3
1962	541.6	2.5	33.3	2.2	199.0	4.9
1963	348.4	5.5	13.3	2.2	64.9	3.1
1964	270.4	17.5	6.8	1.7	30.7	2.4
1965	274.6	17.1	6.2	1.9	20.7	1.7
1966	220.5	26.1	2.7	1.4	9.0	3.3
1967	194.4	0.7	8.0	1.9	20.8	5.5
1968	235.9	13.4	6.7	1.2	16.7	2.1
1969	162.3	18.2	6.2	1.7	14.0	5.4
1970	259.4	1.5	2.6	2.6	16.1	6.6
1971	250.3	7.5	11.2	1.3	27.9	6.6
1972	365.9	2.9	11.3	3.4	47.7	2.0
1973	346.9	3.0	2.5	2.7	12.5	1.3
1974	292.2	15.9	2.6	3.0	12.0	1.5
1975	250.2	13.8	2.6	3.7	13.6	1.9
1976	340.5	8.4	1.7	6.8	15.5	2.8
1977	341.2	13.2	2.8	5.1	25.5	4.3
1978	344.1	14.8	9.5	4.7	44.3	3.7
1979	375.7	38.6	3.9	4.2	40.2	6.4
1980	401.5	2.6	9.2	6.7	57.7	4.6
1981	381.3	29.8	7.2	4.7	42.2	5.0
1982	382.5	3.6	12.7	6.4	48.5	3.1
1983	418.6	24.5	4.2	2.5	35.6	3.8
1984	326.3	36.5	9.5	3.8	55.0	1.7
1985	306.7	21.1	2.9	5.0	19.2	2.6
1986	238.0	5.2	3.5	4.6	16.5	7.6
1987	326.9	1.9	7.1	3.5	36.7	7.6
1988	309.3	18.6	16.8	3.3	58.2	4.8
1989	322.0	5.7	5.5	6.7	35.4	6.3
1990	401.2	25.5	6.1	2.0	43.9	14.4
Median[g]	324.1	13.6	6.9	3.5	26.7	4.1
25%	250.3	3.6	3.7	2.0	16.1	2.1
75%	365.9	21.1	10.3	4.7	43.9	6.3
Trigger	<250.0	>25.0	>25.0	<2.0	<17.0	<3.0

[a] Landings in thousands of metric tons.
[b] Percent by numbers of age 0's in landings.
[c] Percent by numbers of adults (ages 3 and older) in landings.
[d] Estimated numbers of recruits to age 1 in billions.
[e] Estimated mature female biomass (spawning stock biomass or SSB) in thousands of metric tons.
[f] Estimated equilibrium maximum spawning potential based on egg production (for estimated F vs $F = 0$) in percent (includes F at age 0).
[g] Median, 25th, and 75th percentiles based on fishing years from 1965 through 1990, except for p_3+ which is based on fishing years 1955 through 1990.

in the landings may indicate subsequent poor recruitment, and there are no reliable pre-recruit indices of year class strength.

The remaining trigger variables, based on virtual population analysis (VPA), are indicative of basic stock status. Because there are no fishery independent indices of recruitment available for Atlantic menhaden for use in tuning a VPA (Pope and Shepherd 1985), a separable VPA approach (Pope and Shepherd 1982; Clay 1990) was used to bring the VPA estimates of age-specific population size and fishing mortality rates up to the current year of data. The most recent estimates of age-specific population size and fishing mortality rates, and hence recruits to age 1, spawning stock biomass, and percent maximum spawning potential, should be viewed with some skepticism. Without a credible abundance index with which to tune a VPA, the consensus of AMAC was that values of trigger variables based on VPA should only be considered up to 2 or 3 years prior to the most recent data used in the VPA.

Estimates of recruits to age 1 were selected because they indicate directly what will be available to the fishery one year later as age 2 menhaden (the dominant age in the landings). Estimates are available for fishing years 1955 through 1990 in the VPA (Table 1).

Estimates of female spawning stock biomass were selected to represent the availability of spawners in sufficient quantity to produce adequate recruitment. Estimates are also available from 1955 through 1990 (Table 1). The spawning stock biomass is comprised predominantly of age 3 menhaden (Vaughan 1990).

Estimates of percent maximum spawning potential (%MSP) are used widely by the U.S. Fishery Management Councils and Marine Fisheries Commissions to define recruitment overfishing (Vaughan 1990, 1992, Vaughan et al. 1991, 1992). Estimates are calculated in an equilibrium manner from the fishing mortality rates obtained in the VPA for each fishing year from 1955 through 1990 (Table 1) (Gabriel et al. 1989). The low levels of %MSP are of obvious concern, because values between 20% and 30% have been used in a number of management plans by the South Atlantic and Gulf of Mexico Fishery Management Councils. However, values below 10% have been the norm for Atlantic menhaden since 1962. During this time, the stock collapsed and later rebuilt, with recruitment during the 1980's of comparable level to that of the 1950's (Vaughan 1990).

Methods

Virtual population analysis (VPA) is conducted on Atlantic menhaden catch-at-age data from 1955 through 1990 [as described in Vaughan and Smith (1988) and Vaughan (1990) with the addition of 1989 and 1990 data]. The instantaneous natural mortality rate used in the VPA's and in the simulated projections is 0.45/yr. The mean of the age-specific estimates of instantaneous fishing mortality rates (F) for 1980's are used in the projection simulations (Table 2). Starting population age vector is that estimated for 1989 in the VPA. Growth

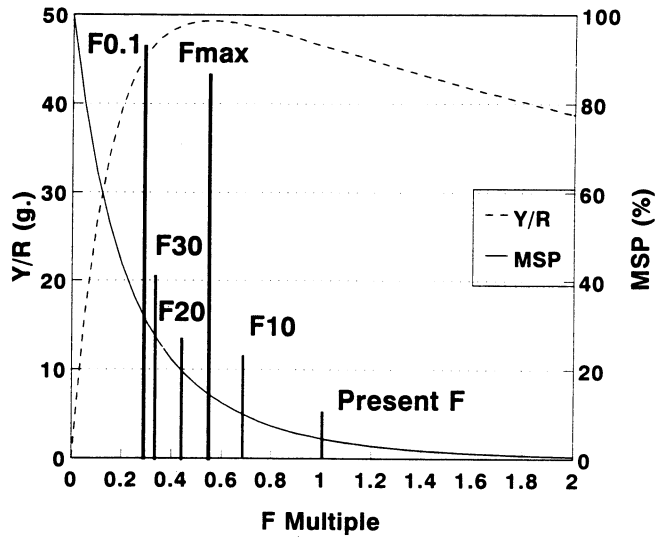

Fig. 1. Critical values of instantaneous fishing mortality rates (F) from yield per recruit (F_{max} and $F_{0.1}$) and from %maximum spawning potential (F_{10}, F_{20}, and F_{30}) for Atlantic menhaden. The estimate of present F is for an age at entry of 0.5 (6 months) and the mean F for the 1980's (Table 2).

in length for the 1980's is represented by a von Bertalanffy equation relating fork length in millimeters (L) with age in years (t):

$$L_t = 355.2 \left(1 - e^{-0.28(t+0.613)}\right), \tag{1}$$

and weight in grams (W) is related to fork length through:

$$W_t = 0.00000556L^{3.2}. \tag{2}$$

Using these estimated F's and growth models, a Ricker-type yield-per-recruit analysis (Y/R) was done, and plotted for the current age at entry of age 0 (Fig. 1). With a sex ratio of 1:1 and female sexual maturity beginning with age 3, a corresponding analysis of maximum spawning potential (%MSP) was done, and also plotted for the current age at entry of 0. The F multiple on the x-axis corresponds to a scalar multiplied by the estimated vector of age- specific F's so that an F multiple of 1 corresponds to current or 1980's mean F (Table 2). Critical values of F are presented from both the Y/R (F_{max} and $F_{0.1}$) and %MSP (F_{10}, F_{20}, and F_{30}) analyses. The critical values from %MSP are those values of F which result in 10, 20, or 30% MSP. Because the Y/R analysis does not include consideration of maintaining sufficient spawning stock to prevent possible recruitment failure, it is of interest to compare these critical values from two different perspectives; $F_{0.1}$ and F_{30} are very similar in magnitude, while F_{max} lies between F_{10} and F_{20}.

Table 2. Mean, minimum, and maximum estimates of age-specific instantaneous fishing mortality rates, F, for Atlantic menhaden for the period 1980–89 from virtual population analysis.

	Instantaneous Fishing Mortality Rates		
Age	Mean	Minimum	Maximum
0	0.09	0.01	0.21
1	0.24	0.06	0.40
2	1.61	1.20	2.20
3	1.12	1.63	1.85
4	1.30	0.97	1.78
5	1.93	1.11	2.81
6	1.31	0.52	1.89
7	0.17	0.00	1.42
8	0.16	0.00	1.59

Simulations that follow are concerned with two approaches to capturing the underlying relationship between an index of spawning stock biomass (S) and an index of recruitment (R). The Ricker spawner-recruit model (Ricker 1975) uses the mathematical relationship:

$$R = \alpha S e^{-\beta S}, \tag{3}$$

which suggests that at moderate values of S, R will reach a maximum, but R will be small at low or high values of S. For the simulations that follow, spawners have been calculated in terms of spawning stock biomass by summing the age-specific products of population numbers and weights (females age 3 and older). Recruits are obtained directly from the VPA for age 0 (that is, at an age of about 6 months). Because the recruits in 1958 (19.0 billion) were almost twice that from any other year class (10.0 billion in 1979), the Ricker spawner-recruit model was estimated for the data from 1955 through 1989 (35 years) with and without the 1958 year class (Fig. 2). The two estimated models are:

$$R = 0.221 S e^{-0.00001101 S} \text{ (with 1958)}, \tag{4}$$

and

$$R = 0.212 S e^{-0.00001109 S} \text{ (without 1958)}, \tag{5}$$

where R is recruits to age 0 in millions and S is spawning stock biomass in metric tons. The use of PROC NLIN (SAS Institute Inc. 1987) with the Marquardt option assumes an additive normal error structure. The residuals based on the Ricker model excluding the 1958 year class tested as not significantly different from a normal distribution ($\mu = 0.5$ billion, $\sigma = 2.8$ billion). Hence, recruitment to age 0.5 is simulated by calculating the spawning stock biomass for a given year, using Eq. (5) to estimate recruitment to age 0.5 for that year, and adding error based on the normal distribution of the residuals estimated in Eq. (5).

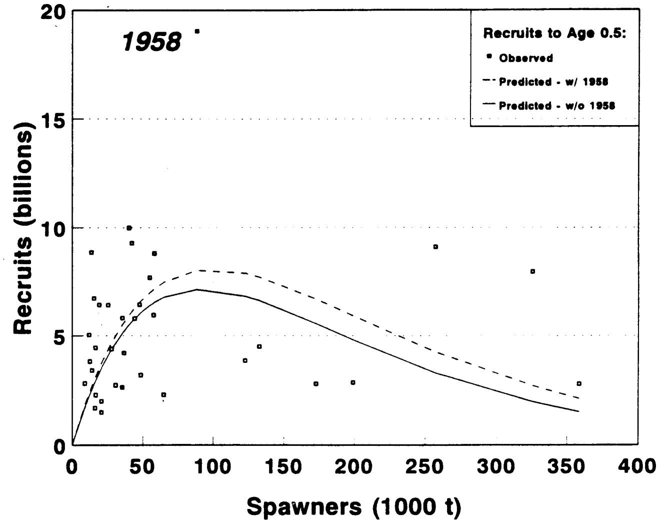

Fig. 2. Observed spawners (weight of females age 3 and older) and resultant recruits to age 0.5 and Ricker spawner-recruit curves for Atlantic menhaden with and without the 1958 year class, 1955–1989.

Table 3. Conditional probabilities from Atlantic menhaden spawners and recruits used in Event Tree relationship. Also given are statistical properties of recruitment categories used to generate specific values for use in simulations.

Spawning Stock Category[a]	Recruits to Age 0.5 Category[b]		
	Low	Medium	High
	Conditional Probabilities		
Low	0.222	0.556	0.222
Medium	0.235	0.530	0.235
High	0.333	0.333	0.334
	Properties of Recruit Categories (billions)		
Mean	2.3	4.5	9.7
Std. Dev.	0.5	1.2	3.6
Minimum	1.5	2.8	6.7
Maximum	2.8	6.4	19.0
Distribution[c]	Gamma	Uniform	Gamma
α	22.34	2.8	7.18
β	0.103	6.5	1.353

[a] The medium category for spawning stock is the interval greater than 16,700 t and less than 64,925 t based on the interquartile range. Low and high categories are below and above these values, respectively.
[b] The medium category for recruits to age 0.5 is the interval greater than 2.8 billion and less than 6.5 billion. Low and high categories are below and above these values, respectively.
[c] Statistical distributions (with parameters α and β) used to simulate actual value of recruitment to age 0.5 given recruit category from Event Tree relationship.

The Event Tree relationship creates discrete categories of spawners and recruits (Table 3). Categories for the spawning stock biomass and recruits to age 0 are based on the interquartile range of the historic data. The spawning stock biomass is

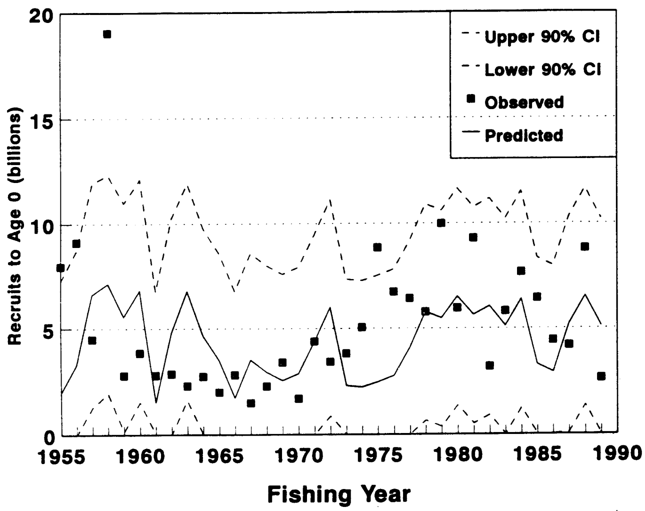

Fig. 3. Observed, predicted and 90% confidence interval about recruits to age 0.5 (6 month) Atlantic menhaden from Ricker spawner-recruit model (estimated without 1958 year class).

considered to be in the "low" category if it is less than or equal to 16,700 t (the 25th percentile), in the "medium" category if it falls between 16,700 t and 64,925 t (the 75th percentile), and in the "high" category if it is greater than or equal to 64,925 t. Similarly, recruits to age 0 are divided into three comparable categories based on its 25th (2.8 billion) and 75th (6.7 billion) percentiles.

The probability of obtaining a particular category of recruit given a particular category of spawning stock biomass forms the basis of the Event Tree relationship. These conditional probabilities are obtained from the historical frequency distribution of these categories for Atlantic menhaden (Table 3). Simulation of the Event Tree process follows two steps. First, given a spawning stock biomass category and the probability of recruitment falling in one of three recruit categories, a uniform distribution is used to assign a recruitment category for a particular year and replicate. Second, statistics calculated on each recruit category are used to generate a quantitative value for use in the population simulations (i.e., uniform distribution for the medium category and gamma distribution for the low and high categories as estimated from the historical data).

Two types of simulations are conducted in this study. The first simulates recruits with error from the historic spawning stock biomass estimated from 1955 through 1989 (100 replicates are made for each relationship). The Ricker model is then estimated (100 times) for each of these data sets generated by the two underlying relationships (Ricker versus Event Tree).

The second set of simulations consists of 12-year population projections (based on the VPA estimates for 1989 from 1990 through 2001). Again, 100 replicates are made for each relationship with the only error introduced where recruits to age 0.5 are estimated from spawning stock biomass. Five sets of parallel simulations are run, based on fishing mortality rates corresponding to five levels of maximum spawning potential. The F multiples and associated MSP are: 1.0 (4.5%), 0.68 (10%), 0.43 (20%), 0.31 (30%), and 0.0 (100%). In addition to the basic population size at age by year, values for the five trigger variables were saved. For comparison the cumulative probability (or risk) of exceeding a particular trigger value are calculated from the projections for each year of the projection. Twelve-year projections were done to represent one full generation (historical data of Atlantic menhaden suggest they lived to about 12 years).

Results

Because error is considerable between the observed and predicted recruits to age 0 based on the Ricker spawner-recruit model, the two relationships (Ricker and Event Tree) were used to recreate or simulate 100 replicates each of recruits from the historic estimates of spawners (Fig. 3). The Ricker model was fit to the 100 replicates of each relationship (200 fits). The observed variability in the Ricker model parameters (α, β in Eq. 3) from the two relationships are compared to the original Ricker model parameters with the 1958 year class excluded (Fig. 4). The Event Tree relationship shows much greater variability in the estimated Ricker parameters than do the estimates from the Ricker relationship. However, there is slightly more bias, based on the difference between the median estimates and the original point estimates, for the Ricker relationship compared to the Event Tree relationship.

Next, the five trigger variables that serve as biological reference points are compared based on simulations from the two relationships with F based on MSP equal to 4.5% in the year 2001. For landings, the trigger is activated when less than or equal to 250,000 t, so risk is defined as the cumulative probability of being less than or equal to a landings value (Fig. 5). Landings in 1990 is fixed by the starting age structure in 1989, with the trigger value of 250,000 t corresponding to 62.5% of the landings estimated for 1990. A value of 0 on the x-axis implies no landings, and a value of 100 implies landings equal to those of 1990. Moving from right to left, the risk curves are initially similar, then the risk associated with the Event Tree relationship is higher, then convergence, and finally the risk associated with the Ricker relationships is higher. At the trigger value of 62.5%, the risk associated with the Event Tree relationship is higher than that associated with the Ricker relationship by about 12%. The risks are almost identical for a decline of about 50% in landings from 1990.

For the percent of age 0 menhaden in the catch in numbers, the trigger is activated if a value greater than 25% is obtained. Risk is defined as the cumulative probability of exceeding a given percent of age 0 menhaden in the catch in numbers (Fig. 6). The risk curves based on both relationships are very similar, with generally slightly higher values from the Ricker relationship, including at the trigger value where the difference is about 5%.

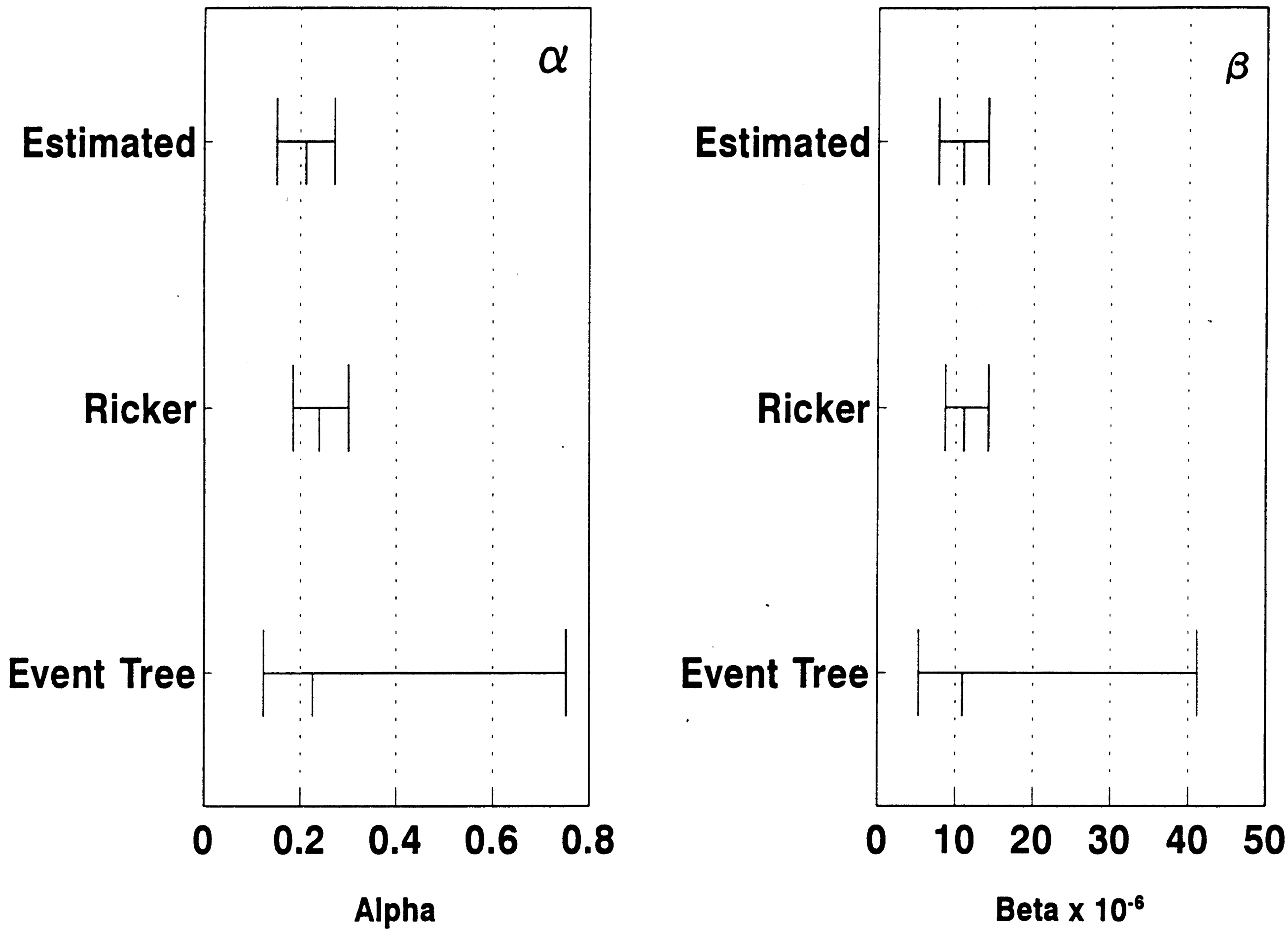

Fig. 4. Estimated Ricker parameters (α and β) with 90% confidence interval for Atlantic menhaden compared for the original estimated parameters, and those from simulated recruits from the Ricker and Event Tree relationships.

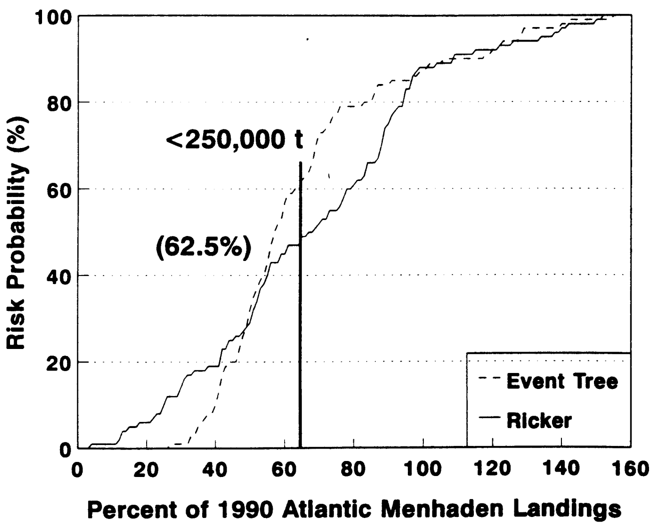

Fig. 5. Cumulative probability (or risk) of Atlantic menhaden landings in 2001 relative to those in 1990 based on Ricker and Event Tree relationships. Trigger value is less than 250,000 t or 62.5% of 1990 predicted landings. Projection instantaneous fishing mortality rate is based on maximum spawning potential of 4.5%.

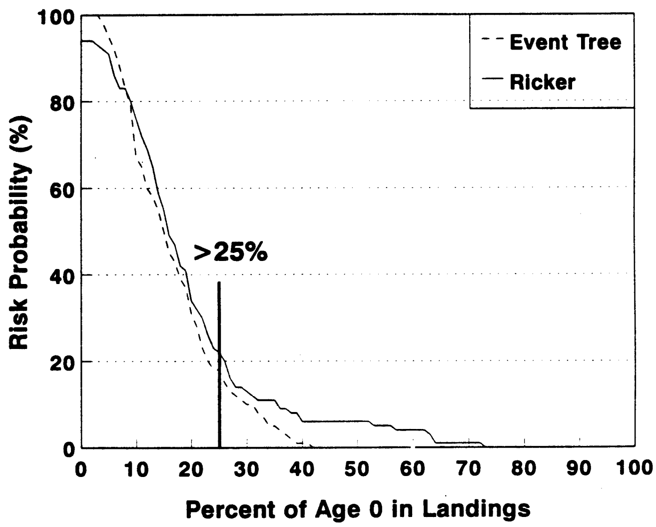

Fig. 6. Cumulative probability (or risk) of proportion of age 0 Atlantic menhaden in the landings by number in 2001 based on Ricker and Event Tree relationships. Trigger value is greater than 25%. Projection instantaneous fishing mortality rate is based on maximum spawning potential of 4.5%.

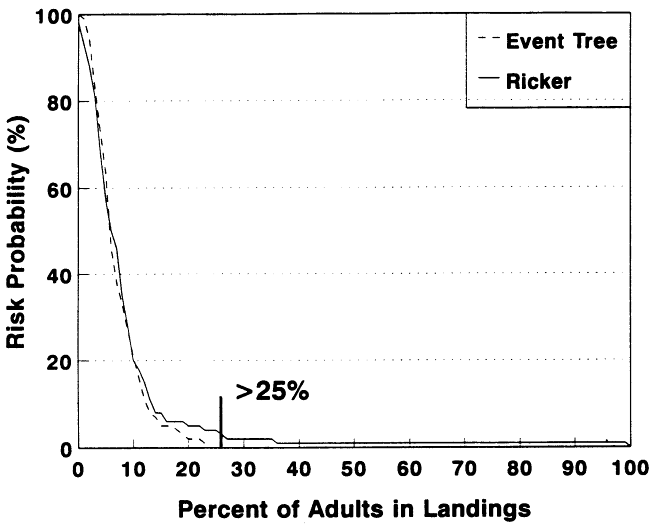

Fig. 7. Cumulative probability (or risk) of proportion of adult (age 3 and older) Atlantic menhaden in the landings by number in 2001 based on Ricker and Event Tree relationships. Trigger value is greater than 25%. Projection instantaneous fishing mortality rate is based on maximum spawning potential of 4.5%.

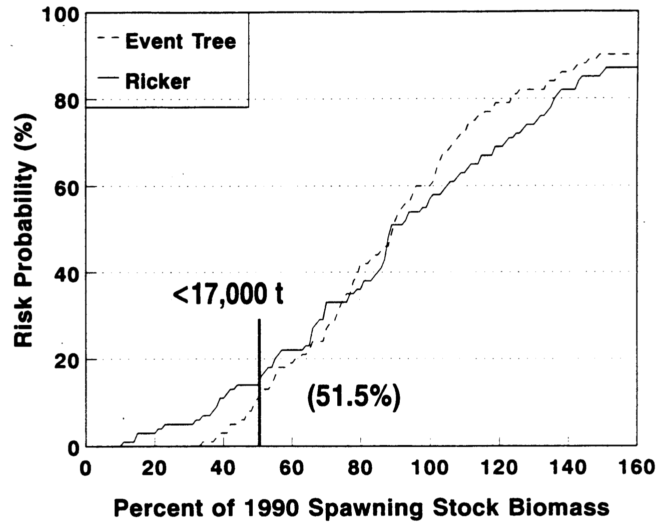

Fig. 9. Cumulative probability (or risk) of decline in Atlantic menhaden spawning stock biomass in 2001 relative to that in 1990 based on Ricker and Event Tree relationships. Trigger value is less than 17,000 t or 51.5% of 1990 spawning stock biomass. Projection instantaneous fishing mortality rate is based on maximum spawning potential of 4.5%.

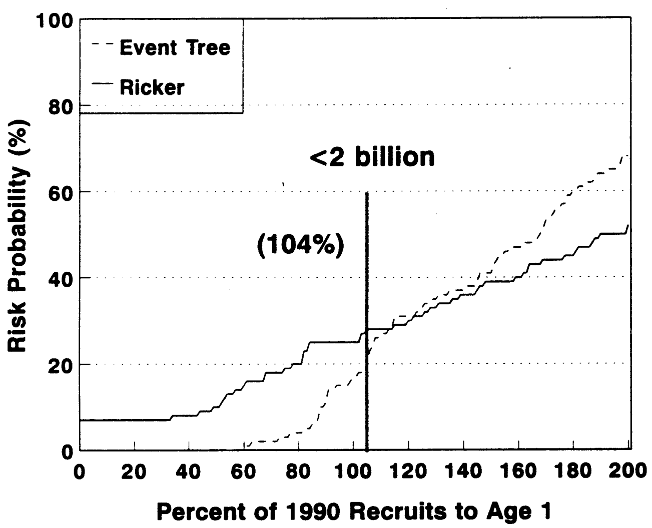

Fig. 8. Cumulative probability (or risk) of decline in recruits to age 1 Atlantic menhaden in 2001 relative to those in 1990 based on Ricker and Event Tree relationships. Trigger value is less than 2 billion recruits or 104% of 1990 recruits to age 1. Projection instantaneous fishing mortality rate is based on maximum spawning potential of 4.5%.

For the percent of adult menhaden (age 3 and older) in the catch in numbers, the trigger is activated if a value greater than 25% is obtained. Risk is defined as the cumulative probability of exceeding a given percent of adults in the catch in numbers (Fig. 7). The risk curves based on both relationships are very similar, with generally slightly higher values from the Ricker relationship, including at the trigger value where the difference is about 4%.

For the recruits to age 1, the trigger is activated when it falls below 2 billion or about 104% of the recruits to age 1 in 1990. The recruits to age 1 in 1990 is obtained deterministically from the recruits to age 0 in 1989 (part of the starting age structure). Risk is defined as the cumulative probability of a value less than or equal to a given value of recruitment (Fig. 8). The risk associated with the Ricker relationship is uniformly larger than that associated with the Event Tree relationship for recruitment values less than the trigger, and the difference is between 7 and 8% at the trigger value.

For the spawning stock biomass, the trigger is activated when it falls below 17,000 t or about 51.5% of the spawning stock biomass in 1990. Spawning stock biomass in 1990 through 1992 is fixed by the initial age structure in 1989. Simulated recruits to age 0 in 1990 do not appear in the spawning stock until 1993 as age 3 menhaden. Risk is defined as the cumulative probability of a value less than or equal to a given value of spawning stock biomass (Fig. 9). The risk associated with the Ricker relationship for low levels of spawning stock biomass is somewhat larger than that associated with the Event Tree relationship for spawning stock biomass, and the difference is about 3% at the trigger value.

Next, annual median spawning stock biomass from the 12-year population projections based on the two relationships are compared for five levels of F (Fig. 10). The Ricker model seemingly prevents the spawning stock biomass from getting very large when F equals 0 (MSP = 100%) (Fig. 10a). Hence, the ratio of the median spawning stock biomass for the first four levels (4.5, 10, 20, and 30) to that for $F = 0$ in 2001 are larger than suggested by the density independent approach used in formulating %MSP. Median spawning stock biomass from the Event Tree relationship is not similarly constrained when $F = 0$ (Fig. 10b), although it is constrained by the

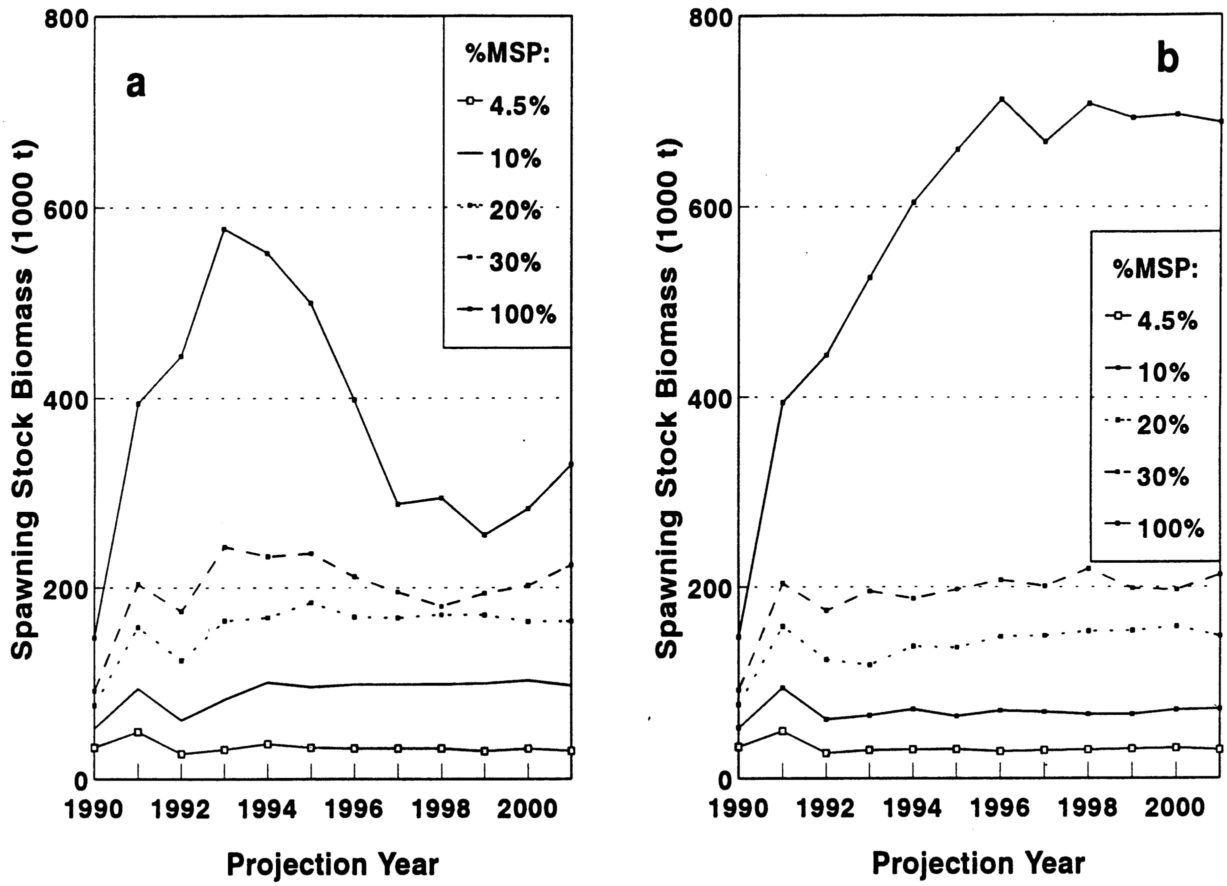

Fig. 10. Median spawning stock biomass of 100 replicate population projections of 12 years (1990–2001) for the Ricker (a) and Event Tree (b) relationships with projection instantaneous fishing mortality rate based on 5 levels of maximum spawning potential (4.5, 10, 20, 30, and 100%).

gamma distribution placed on the high category of recruits to age 0. The ratio of spawning stock biomass in 2001 closely approximates that suggested by %MSP. Similar values of median spawning stock biomass for values of MSP less than or equal to 30% are obtained from the two relationships.

Finally, the risk of spawning stock biomass is compared for the five levels of MSP in the year 2001 between the two simulation relationships (Fig. 11). For the simulations based on the Ricker relationship, there is a large drop in risk of a decline in spawning stock biomass between F based on an MSP equal to 4.5% and MSP equal to 10% and considerable overlap of the risk curves for MSP of 10%, 20%, and 30% (Fig. 11a). However, for the simulations based on the Event Tree relationship, there is a more gradual decline in risk with decreasing F's associated with increasing MSP's (Fig. 11b).

Discussion and Conclusions

In this section, I begin by discussing several questions that arose in the course of this study. This is followed by a discussion of what conclusions relevant to management of the Atlantic menhaden might be drawn from these simulations.

While setting up the simulations, the question arose as to how many variables should be simulated with error. Because the purpose of this study is to compare the relative risks associated with the two relationships for spawning stock biomass with subsequent recruits, error was only simulated in obtaining recruits to age 0 from spawning stock biomass. The simulation of additional error in other population model parameters would only tend to obscure the differences between the two relationships.

The sensitivity of the estimates of risk to underlying probability distributions was not explored. In this analysis, error for the Ricker and Event Tree relationships was simulated using the normal, uniform, and gamma distributions. How sensitive the final results might be to these assumptions has not been explored and is open to further study by simulations.

Is there an underlying mechanistic model (i.e., the Ricker model) that relates spawners and subsequent recruits for predicting future Atlantic menhaden populations? Is this relationship simply obscured by large environmental variability as is usually suggested? Or is the use of conditional probabilities more appropriate? As noted in the foregoing simulations, there are differences in the risks, but simulations such as those described here are not able to address the appropriateness of the two relationships.

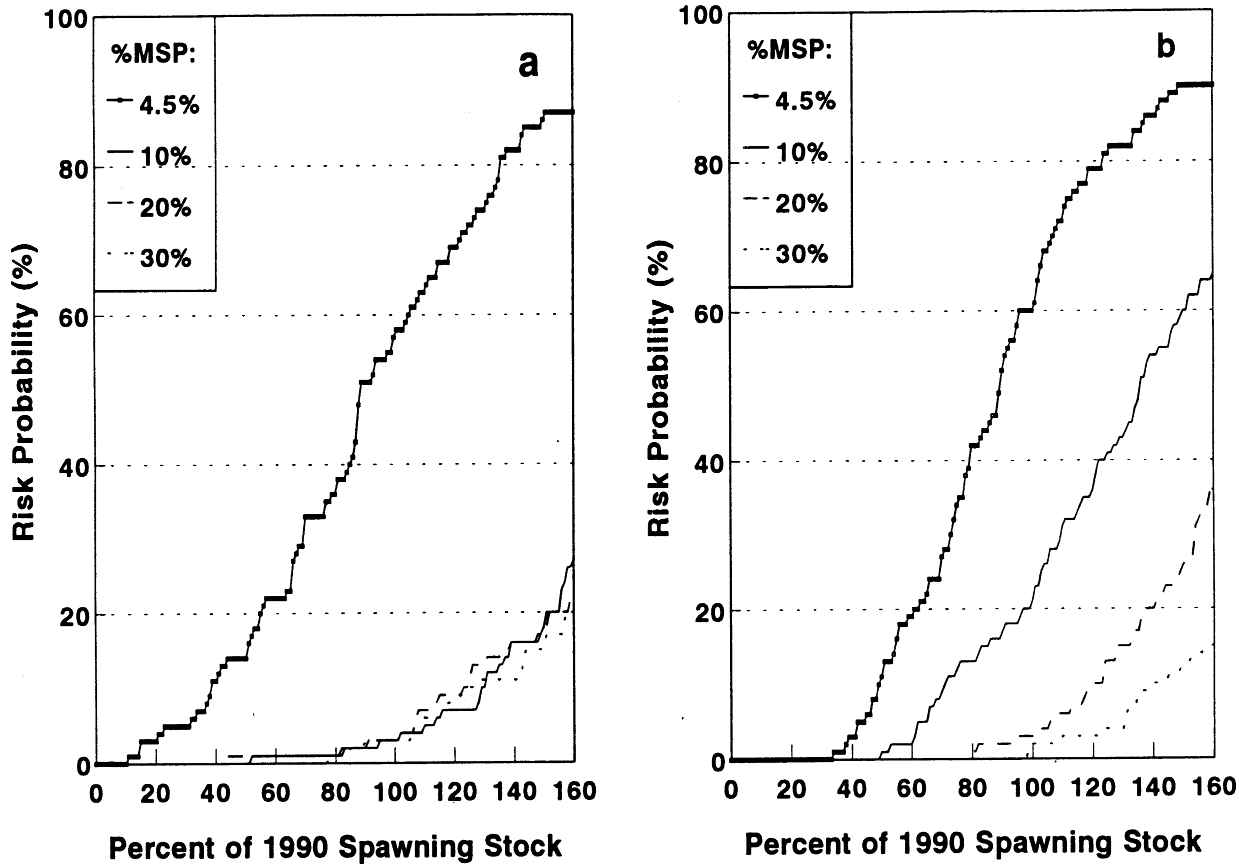

Fig. 11. Cumulative probability (or risk) of decline in Atlantic menhaden spawning stock biomass in 2001 (relative to 1990) for the Ricker (a) and Event Tree (b) relationships with projection instantaneous fishing mortality rate based on 4 levels of maximum spawning potential (4.5, 10, 20, and 30%).

It is interesting to note that simply by applying the conditional probabilities of the Event Tree relationship to the historical set of spawning stock biomass to obtain corresponding recruits to age 0, relatively unbiased estimates of the Ricker model are obtained when compared to the original data (Fig. 4). However, as should be expected the variability in estimates of the Ricker parameters is much larger when simulated from the Event Tree relationship as compared with the variability when simulated from the Ricker relationship. The latter variability is very similar to that found in the original Ricker nonlinear regression.

The greatest differences in risk at the trigger values were found for landings in weight and recruits to age 0 (Figs. 5 and 8). The landings in weight is the only trigger variable for which the risk is greater for the Event Tree relationship at the trigger value (12% at 250,000 t or 62.5% of landings in 1990). For reductions in landings below about 50% from the 1990 level, risk associated with the Ricker relationhip was higher; while reductions in landings between about 60% and 100% from the 1990 levels, risk associated with the Event Tree relationship was higher. For the remaining trigger variables, the risk associated with the Ricker relationship is uniformly greater for more excessive levels of the trigger value (i.e., larger percents of age 0 and adults in landings by number, and smaller values of recruits and spawners).

It is not surprising that there is a large difference in risk for the recruits to age 1 (7 to 8% at the trigger value of 2 billion or 104% of recruits in 1990), because that is the level at which basic uncertainty is being simulated. Greater differences in risk would be expected in landings compared with spawning stock biomass (only about 3% at 17,000 t or 51.5% of 1990 level), because the latter trigger variable contains fewer ages (3–8 compared to 1–8). Small differences in risk are associated with the two triggers comparing age 0 and adult menhaden in the landings in numbers; 5% versus 4%.

With respect to the risk of a particular trigger value being exceeded (i.e., activated), the risk associated with the Ricker relationship appears to be activated more often. Activation of the recruit and spawning stock trigger variables are by the nature of the variables indicative of poor stock health, whereas activation of the first three triggers may give "false firings". But what should be of particular interest to managers is the difference in advice that might be suggested when comparing the risk curves based on different levels of F associated with maximum spawning potential (Fig. 11).

For the Ricker relationship, a risk of a decline in landings or spawning stock biomass drops precipitously from an MSP of 4.5% to 10%. For greater improvements in MSP, there is no apparent gain in reduction of risk remaining to be accrued. A quite different picture arises from the Event Tree relationship: a more gradual decline in risk is observed with the decrease in F associated with increasing MSP from 4.5% to 10% to 20% and to 30%. The mathematical nature of the Ricker model is undoubtedly the cause for this difference (compare Figs. 10a and 10b for median values of spawners at the MSP of 100%).

In conclusion, if the Ricker relationship best represents the underlying relation for spawners with recruits, then a goal for MSP higher then 10% may not be needed. However, if the Event Tree relationship better represents the underlying spawner-recruit relationship, then a goal greater than 10% MSP may be needed. Unfortunately, there is no absolute way to determine which relationship best represents the future course of the Atlantic menhaden stock. Regardless of which relationship is more realistic, there is substantial reductions in risk by adoption of a 10% MSP as the management goal for Atlantic menhaden.

Acknowledgements

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